

Wavelength standards for optical communications^{*}

Sarah L. Gilbert,[†] William C. Swann, and Tasshi Dennis
National Institute of Standards and Technology

ABSTRACT

We review wavelength accuracy and calibration issues for wavelength division multiplexed (WDM) optical fiber communication and describe our work on wavelength calibration references. We have developed wavelength references for National Institute of Standards and Technology (NIST) internal calibration and transfer standards to help industry calibrate their instrumentation. The transfer standards are NIST Standard Reference Materials that utilize the absorption lines of acetylene and hydrogen cyanide in the 1500 nm region. Two higher accuracy references for NIST internal use are based on laser stabilization to absorption lines of rubidium (at 1560 nm) and methane (at 1314 nm). We are developing calibration references for the WDM L-band (~1565–1625 nm) and are investigating references for the 1300–1400 nm region.

Keywords: atomic spectroscopy, molecular spectroscopy, optical fiber communications, pressure shift, Standard Reference Material, wavelength calibration, wavelength division multiplexing, wavelength standards, WDM

1. INTRODUCTION

Wavelength division multiplexing (WDM) in optical fiber communication systems increases bandwidth by using many wavelength channels. Current WDM systems typically employ 50 or 100 GHz channel spacing (0.4 or 0.8 nm, respectively) in the 1540–1560 nm region, but narrower channel spacing may be implemented soon. Wavelength division multiplexing will likely expand into other wavelength regions as well, possibly covering the entire range from about 1280 to 1630 nm. At the same time, systems are pushing toward higher bit rates, with 10 Gb/s systems currently being introduced and 40 Gb/s systems under development.

Wavelength stability of sources and components and wavelength calibration of equipment are essential for WDM systems. Instruments such as optical spectrum analyzers, tunable lasers, and wavelength meters are used to characterize WDM system components and measure the channel wavelengths. Although most WDM applications do not require that equipment be calibrated to an uncertainty better than about 0.5 GHz, some applications, particularly in R&D laboratories, require higher accuracy.

Atomic and molecular absorption lines provide wavelength calibration references that are very stable under changing environmental conditions. Molecules such as acetylene and hydrogen cyanide have distinctive absorption features in the 1500 nm region due to rotational-vibrational transitions; these transitions are combination or overtone bands that can be probed directly. Atomic transitions in the 1300–1600 nm region are between excited states and thus require initial excitation by a laser¹ or electric discharge.² There is only one gas laser reference line: the 1523 nm helium-neon laser. Other atomic or molecular references can be realized by frequency doubling 1300–1600 nm light to probe atomic transitions in the 650–800 nm region.³ Below we

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[†] sgilbert@boulder.nist.gov; ph. (303)497-3120, fax (303)497-7621; <http://www.boulder.nist.gov/div815/81503.htm>; NIST, M/S 815.03, 325 Broadway, Boulder, Colorado 80305 USA

describe our research on wavelength calibration references based on atomic and molecular absorption lines.

2. NIST WAVELENGTH CALIBRATION REFERENCES

We have developed both moderate accuracy transfer standards and higher accuracy wavelength references for WDM. The transfer standards, which incorporate molecular gas absorption cells, are simple devices to help industry calibrate instrumentation. The higher accuracy references are lasers stabilized to methane and rubidium absorption lines; these references allow us to check the accuracy of our wavelength meter.

2.1 1510–1560 nm Transfer standards

Our moderate accuracy references are NIST Standard Reference Material (SRM) transfer standards based on rotational-vibrational transitions of acetylene, $^{12}\text{C}_2\text{H}_2$ (SRM 2517a), and hydrogen cyanide, $\text{H}^{13}\text{C}^{14}\text{N}$ (SRM 2519). The $\nu_1 + \nu_3$ combination band of acetylene (Fig. 1) has more than 50 strong absorption lines in the 1510-1540 nm region. The absorption lines of the $2\nu_3$ overtone transition of hydrogen cyanide (Fig. 2) are better placed for current WDM applications, with about 50 lines in the 1530-1565 nm region.

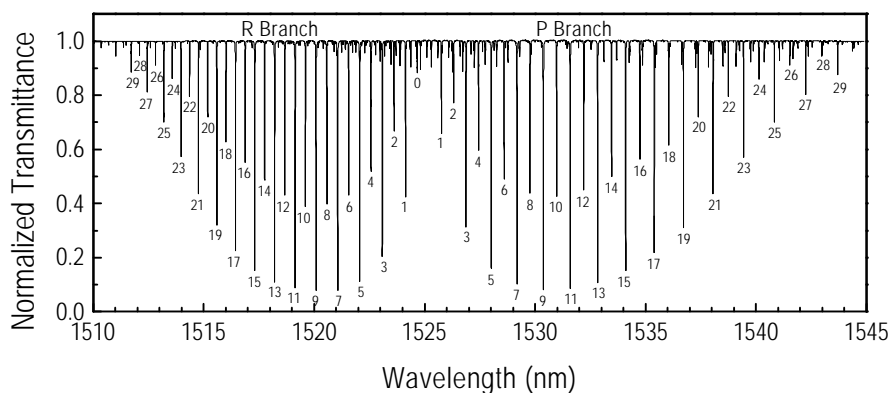


Figure 1 Spectrum of the acetylene $^{12}\text{C}_2\text{H}_2$ $\nu_1 + \nu_3$ band obtained by scanning a tunable diode laser and measuring the laser power transmitted through a 5 cm long absorption cell filled to a pressure of 6.7 kPa (50 Torr).

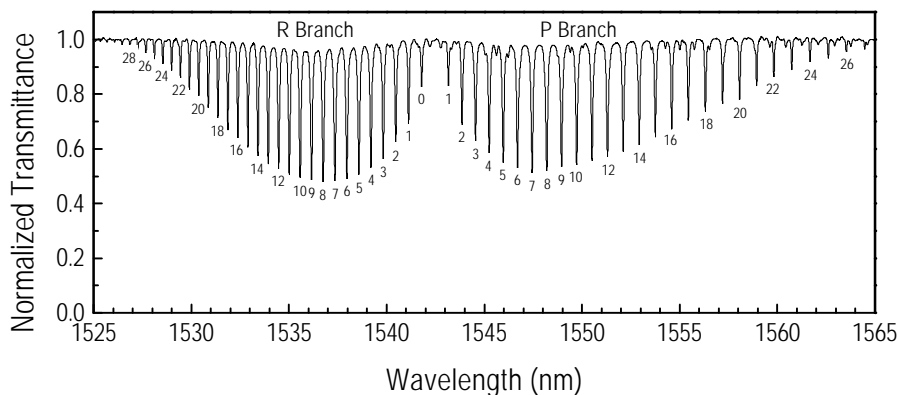


Figure 2 Normalized spectrum of the hydrogen cyanide $\text{H}^{13}\text{C}^{14}\text{N}$ $2\nu_3$ band obtained by passing LED light through a SRM unit and recording the spectrum of the transmitted light using an optical spectrum analyzer with 0.05 nm resolution. The HCN gas pressure is 13 kPa (100 Torr) and the optical path length through the gas is 22.5 cm.

The Standard Reference Materials were designed for calibrating wavelength-measuring instruments such as optical spectrum analyzers and wavelength meters. The SRM units are optical-fiber-coupled with singlemode fiber, and the spectrum can be observed using a broadband source (such as a light-emitting diode or amplified spontaneous emission source) or a tunable laser. Single-wavelength calibrations using a single line, and scan linearity measurements using multiple lines can be made. NIST has evaluated the uncertainty of the line centers and provides certified wavelength values. Each SRM unit is measured at NIST to assure that it has sufficient gas purity and contains the correct pressure.

The vacuum wavelengths of the acetylene line centers have been measured with a quoted uncertainty of 1.2×10^{-6} nm,⁴ and the hydrogen cyanide line centers have been measured with a quoted uncertainty of 1.2×10^{-4} nm.⁵ Although molecular structure is relatively insensitive to changes in environmental conditions, it is not completely immune, and slight shifts of line centers can occur under certain conditions. The largest potential source of line shift is due to energy level shifts caused by the interaction of the molecules during collisions. This collision-induced line shift (the pressure shift) increases linearly with pressure. The line center values given in Refs. 4 and 5 are for very low pressure conditions and are applicable, at the quoted uncertainty, only to that situation. To provide sufficient signal when used with a 0.1 nm resolution instrument, such as an optical spectrum analyzer, the gases in the SRMs are at moderate pressures [6.7 kPa (50 Torr) for acetylene, and 13.3 kPa (100 Torr) for hydrogen cyanide]. Since our goal was to certify these SRM references with an uncertainty of less than 1 pm, we measured the pressure shift for both acetylene and hydrogen cyanide.

A schematic diagram of our pressure shift measurement apparatus is shown in Fig. 3. Light from a tunable diode laser is sent through two absorption cells simultaneously, and the transmission through each cell is monitored by detectors. For the acetylene measurement, one cell contains acetylene gas at a relatively low pressure (6.7 kPa) and the other contains either intermediate pressure (29.7 kPa) or high pressure (66 kPa). A third detector monitors the laser power, and a wavelength meter measures the laser's wavelength with an uncertainty of 1 part in 10^7 . A computer controls the laser wavelength scan and records the readings of the three detectors and wavelength meter.

Figure 4 shows spectra of line P4 of acetylene $^{12}\text{C}_2\text{H}_2$, obtained using the low and high pressure cells. The pressure broadening in the high pressure spectrum is obvious. We are primarily interested in the relative shift between the line centers in the low pressure and high pressure cells. Fifteen lines were scanned using these cells and 13 of these lines were also scanned using the low and intermediate pressure cells. Details of our pressure shift measurement and line fitting procedure are given in Ref. 6. We found that the pressure shift varies with line number, as shown in Fig. 5, but is less than 0.3 pm for the 6.7 kPa (50 Torr) SRM cell pressure. For the acetylene SRM certification, we adjusted the literature line center values for the pressure shift and certify the wavelengths of these 15 lines with an expanded uncertainty (coverage factor $k = 2$, that is, $\pm 2\sigma$) of 0.1 pm. The remainder of the lines in the band are certified with uncertainties ranging from 0.3 to 0.6 pm.

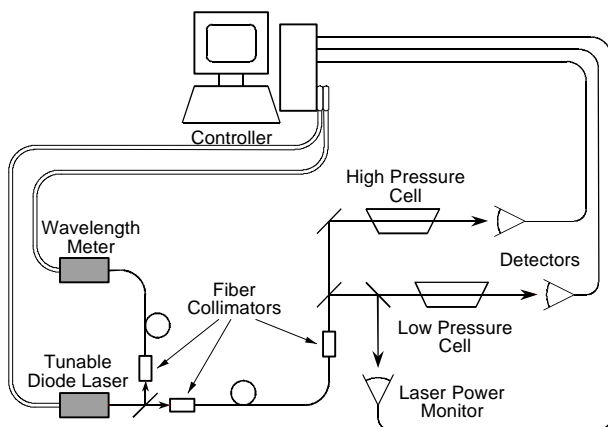


Figure 3 Diagram of pressure shift measurement apparatus.

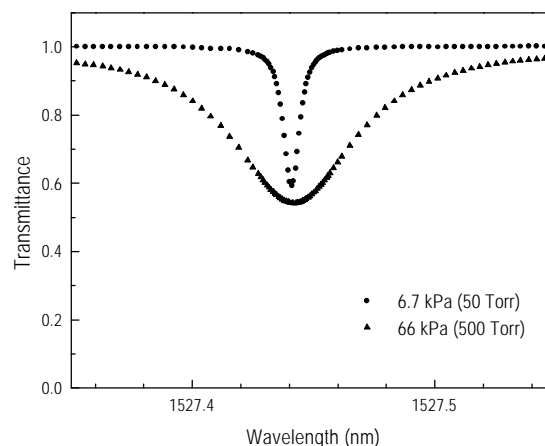


Figure 4 Tunable diode laser scan of $^{12}\text{C}_2\text{H}_2$ line P4 showing the transmittance through the low pressure and high pressure cells.

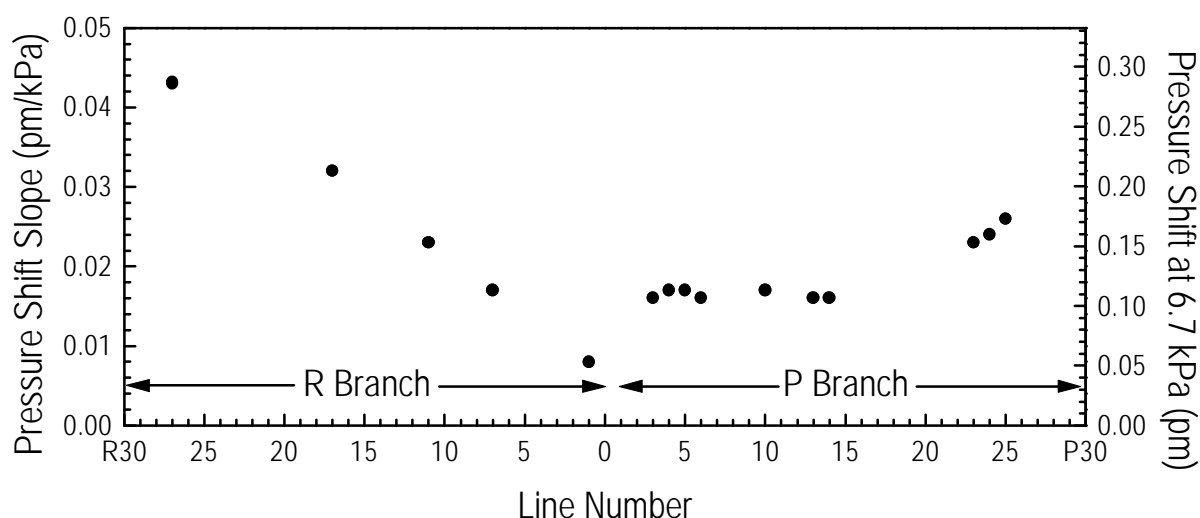


Figure 5 Plot of the pressure shift slope and pressure shift at the SRM pressure of 6.7 kPa (50 Torr) versus line number for the R and P branches of the $^{12}\text{C}_2\text{H}_2$ $\nu_1 + \nu_3$ band.

We found that the pressure shift in hydrogen cyanide is more significant (as large as 2 pm for the SRM pressure) and has a larger variation with line number. We have measured the line centers and pressure-induced shifts of 21 hydrogen cyanide lines and certify their wavelengths with an expanded uncertainty of 0.6 pm. The remainder of the lines in the band are certified with an expanded uncertainty of 3 pm, where this uncertainty is dominated by the pressure shift uncertainty.⁷ Since the cells containing the gases are sealed, environmental conditions will cause very little change in the line centers. Temperature changes will have a slight effect on the collision rate (and hence the pressure shift), but this effect is much smaller than the uncertainties quoted above for the certified line centers.

2.2 High Accuracy References

To make line center measurements and evaluate the SRM units, we need higher accuracy internal references to check the accuracy of our wavelength meter. We developed a high accuracy reference based on high-resolution spectroscopy of the 780 nm rubidium $5S_{1/2}$ to $5P_{3/2}$ transition using frequency-doubled light. We amplify 1560.5 nm diode laser light using an erbium-doped fiber amplifier and frequency-double it in a periodically poled lithium niobate (PPLN) crystal. We use the resultant 780 nm light to conduct saturated absorption spectroscopy on the rubidium transitions. The hyperfine components of these transitions are less than 10 MHz wide and their absolute frequencies have been measured with an uncertainty of less than 0.5 MHz.⁸ We use these references to calibrate our wavelength meter by stabilizing the frequency-doubled source to several different hyperfine components of the ^{87}Rb transition and comparing our wavelength meter readings to the literature values multiplied by 2. Since the lines are very narrow, the absolute stability of the locked laser is much better than the quoted wavelength meter uncertainty of 1×10^{-7} (about 20 MHz at 1560 nm). From measurements taken before and after our pressure shift scans, we found that the wavelength meter reading was offset by -0.20 ± 0.06 pm ($+25 \pm 8$ MHz). We repeat these measurements periodically to ensure continued accuracy during SRM certification.

The upper section of Fig. 6 shows the methane-stabilized source we constructed as a high accuracy reference in the 1300 nm region. After optical isolation to prevent feedback, the light is split and the smaller portion (15 %) is passed through a gas absorption cell. The transmittance signal is normalized to a reference detector to remove the spectral dependence of the diode laser and isolators. Using frequency modulation and phase-sensitive detection, we stabilize the laser to the center of a methane line.

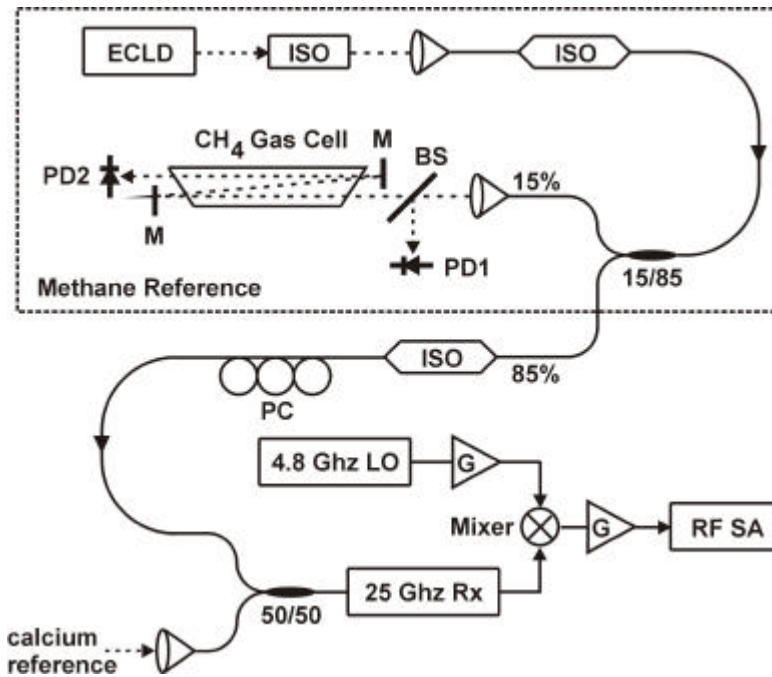


Figure 6 Setup for laser stabilization to methane and beat-note measurement with calcium reference: ECLD, extended cavity laser diode; ISO, isolator; BS, beamsplitter; M, mirror; PD, photodiode; PC, polarization controller; LO, local oscillator; Rx, photoreceiver; SA, spectrum analyzer.

The larger portion (85 %) of the split laser light is available for the calibration of laboratory equipment. We have performed a beat-note measurement with a laser referenced to the calcium frequency standard developed and maintained by the NIST Time and Frequency Division⁹ and have measured a methane transition at 1314 nm with an uncertainty of less than 5 MHz (0.03 pm). This methane-stabilized laser now serves as a NIST internal calibration reference.

2.3 L-band Wavelength References

Wavelength division multiplexing will be implemented in the WDM L-band (approximately 1565–1625 nm) in the near future. We examined a number of molecules as potential references for this region. Hydrogen and deuterium halides generally have strong lines and simple spectra, but of these only hydrogen iodide (HI)¹⁰ has spectral lines in the L-band. Unfortunately, HI has several drawbacks: the spectrum (lines between 1534 and 1595 nm) only partially covers the L-band, some of the lines have significant substructure due to the electric-quadrupole hyperfine interaction, and the gas is difficult to work with due to its reactivity and tendency to decompose. We also investigated various hydrocarbons, halogenated hydrocarbons, and other gases containing one or more CH bonds, since overtones of the CH bond's vibrational energy have spectra near 1550 nm. Although some of the spectra were in the correct location, we found that they were either too weak or highly convoluted, containing hundreds of overlapping lines. These are typically not simple linear molecules, and off-axis vibrations cause complicated spectra.

We have found that carbon monoxide provides suitable wavelength-reference absorption lines in the L-band. The carbon 12 isotope ($^{12}\text{C}^{16}\text{O}$) provides about 40 lines between 1560 and 1595 nm (see Fig. 7), and $^{13}\text{C}^{16}\text{O}$ has about 35 lines between 1595 and 1628 nm.¹¹ These lines are weaker than the absorption lines in either acetylene or hydrogen cyanide, but are not too weak to be considered for a portable wavelength calibration device.

We have built a prototype wavelength SRM device based on carbon monoxide. The unit contains a 20 cm long borosilicate glass cell filled to a pressure of 133 kPa (1000 Torr). This

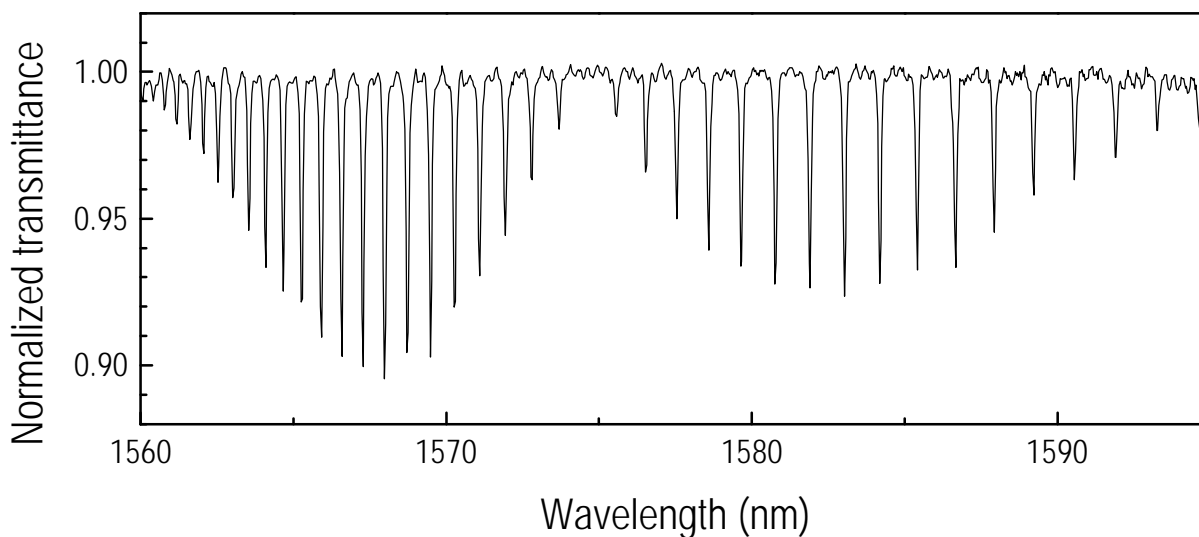


Figure 7 Normalized carbon monoxide $^{12}\text{C}^{16}\text{O}$ spectrum obtained by passing LED light through a prototype SRM unit and recording the spectrum of the transmitted light using an optical spectrum analyzer with 0.05 nm resolution. The CO gas pressure is 133 kPa (1000 Torr) and the optical path length through the gas is 80 cm.

provides lines with depths of 5 % to 10 % and widths of 0.04 nm to 0.05 nm, suitable for typical spectrum analyzer or laser calibration. Light from a singlemode optical fiber is collimated into a free beam, and then passes through the cell in a four pass re-entrant configuration. This provides a total absorption path of 80 cm inside a package with an exterior length of less than 30 cm. The re-entrant configuration requires that the device be used with a 3 dB coupler or an optical circulator. The same packaging is suitable for either $^{12}\text{C}^{16}\text{O}$ or $^{13}\text{C}^{16}\text{O}$. We are presently investigating the pressure shift and other properties of $^{12}\text{C}^{16}\text{O}$, and plan a similar investigation of $^{13}\text{C}^{16}\text{O}$.

3. CONCLUSIONS

Wavelength calibration of equipment in the near infrared is essential for WDM systems. We have developed convenient transfer standards for wavelength calibration in the 1510–1560 nm region and are developing transfer standards for the 1565–1630 nm region. Wavelength division multiplexing will likely expand into the 1300 and 1400 nm regions, and it will be very difficult to find absolute references for this wide wavelength range. One possibility is the use of calibrated artifact references, such as etalons¹² or fiber Bragg gratings.¹³ Artifacts can provide references at arbitrary wavelengths, but they suffer from large temperature, strain, and pressure sensitivity. Passive or active thermal stabilization can substantially reduce this variability, and the artifacts can be referenced to atomic or molecular standards.^{12,13}

In order to characterize the transfer standards, we need internal calibration references with higher accuracy (few megahertz) throughout the near IR region. We have established references at 1314 nm and 1560 nm and plan to develop other references in the 1280–1630 nm region in collaboration with the NIST Time and Frequency Division.

REFERENCES

1. S.L. Gilbert, "Frequency Stabilization of a Fiber Laser to Rubidium: a high accuracy 1.53 μm wavelength standard," in *Frequency Stabilized Lasers and Their Applications*, Proc. SPIE 1837, 146-153 (1993).
2. Y.C. Chung, "Frequency-Locked 1.3- and 1.5- μm Semiconductor Lasers for Lightwave Systems Applications," J. Lightwave Technol. **8**, 869-876 (1990).
3. A. Bruner et al., "Frequency stability at the kilohertz level of a rubidium-locked diode laser at 192.114 THz," Appl. Opt. **37**, 6410-6414 (1998); A. Bruner et al., "Frequency stabilization of a diode laser at 1540 nm by locking to sub-Doppler lines of potassium at 770 nm," Appl. Opt. **37**, 1049-1052 (1998).
4. K. Nakagawa, M. de Labacherie, Y. Awaji, and M. Kourogi, "Accurate optical frequency atlas of the 1.5- μm bands of acetylene," J. Opt. Soc. Am. B **13**, 2708-2714 (1996).
5. H. Sasada and K. Yamada, "Calibration lines of HCN in the 1.5- μm region," Appl. Opt. **29**, 3535-3547 (1990).

6. W.C. Swann and S.L. Gilbert, "Pressure-induced shift and broadening of 1510–1540-nm acetylene wavelength calibration lines," J. Opt. Soc. Am. B **17**, 1263-1270 (2000); S.L. Gilbert and W.C. Swann, "Acetylene $^{12}\text{C}_2\text{H}_2$ Absorption Reference for 1510nm to 1540 nm Wavelength Calibration – SRM 2517a," Natl. Inst. Std. Technol. Spec. Publ. 260-133 (revised 2000), In Press.
7. S.L. Gilbert, W.C. Swann, and C.M. Wang, "Hydrogen Cyanide $\text{H}^{13}\text{C}^{14}\text{N}$ Absorption Reference for 1530–1560 nm Wavelength Calibration – SRM 2519," Natl. Inst. Std. Technol. Spec. Publ. 260-137 (1998).
8. G.P. Barwood, P. Gill, and W.R.C. Rowley, "Frequency measurements on optically narrowed Rb-stabilised laser diodes at 780 nm and 795 nm," Appl. Phys. B **53**, 142-147 (1991); J. Ye, S. Swartz, P. Jungner, and J. Hall, "Hyperfine structure and absolute frequency of the ^{87}Rb $5\text{P}_{3/2}$ state," Opt. Lett. **21**, 1280-1282 (1996).
9. C.W. Oates, E.A. Curtis, and L. Hollberg, "Improved short-term stability of optical frequency standards: approaching 1 Hz in 1 s with the Ca standard at 657 nm," Opt. Lett. **25**, 1603-1605 (2000).
10. F. Bertinetto, P. Gambini, R. Lano, and M. Puleo, "Stabilization of the emission frequency of 1.54 μm DFB laser diodes to hydrogen iodide," IEEE Photon. Technol. Lett. **4**, 472-474 (1993).
11. L.S. Rothman et al., "The Hitran molecular database: editions of 1991 and 1992," J. Quant. Spectrosc. Rad. Transf. **48**, 469-507 (1992).
12. D.A. Humphreys, "Accurate wavelength calibration for optical spectrum analyzers," in *Technical Digest - Symposium on Optical Fiber Measurements*, Natl. Inst. Std. Technol. Spec. Publ. 905, pp. 97-100 (1996).
13. W.C. Swann, M.A. Hubbard, and S.L. Gilbert, "Hybrid multiple wavelength reference using fiber gratings and molecular absorption," in *Proc., Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, OSA Technical Digest (Optical Society of America, Washington DC, 1999), pp. 63-65.